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The Tangled History of the Nonlocality Issue in Quantum Mechanics *

Michael Redhead

Abstract

* This paper is an updated and revaluated version of material originally presented in Redhead (1991) and Redhead and La Rivière (1997).

Anne: Please place this at the beginning of the footnote on p. 37

Version A

~~Nonlocality in Quantum Mechanics~~

There are many purported proofs of nonlocality in quantum mechanics (QM). A representative selection of such proofs are critically examined so as to expose as precisely as possible the assumptions on which they are based.

This paper is predicated on the assumption that nonlocality in the sense of instantaneous causal action-at-a-distance is to be avoided if at all possible, on pain of violating at any rate the spirit of special relativity (SR). Some authors, such as Bohm, have advocated interpretations of QM that do involve this type of nonlocality, in which SR is rescued as a phenomenological principle valid at the statistical level.

The Bohm interpretation is also deterministic. It is therefore objectionable on two counts:

1. the scientific count of fudging the relativity issue;
2. the theological count of not allowing 'room' for Divine Action.

I shall therefore be looking particularly at indeterministic settings and examining the question of whether proofs of objectionable forms of nonlocality can be blocked, thus remedying the two defects in Bohm-type interpretations noted above (despite their undoubted attraction in terms of picturability [trajectories] and the absence of a measurement problem).

Recent work on demonstrations of nonlocality in the context of relativistic quantum ~~field theory~~ quantum mechanics are also examined. The conclusion here is that an indeterministic framework in which measurements actualise potentialities (as advocated by Shimony, for example) offers the best prospect for avoiding the twin objections to the Bohm approach.

However, cosmological considerations tell against such an approach and may favour the realist-holistic treatment advocated in Redhead's 1995 book From Physics to Metaphysics.

NONLOCALITY IN QUANTUM MECHANICS

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The object of the present paper is to survey, in a relatively non-technical fasion, some of the recent literature on the issue of nonlocality in quantum mechanics. The emphasis will be on the motivating ideas behind the proofs, rather than the details of the mathematics, which will be largely taken on trust.

Introduction

It is often maintained that quantum mechanics (QM) is obviously 'nonlocal', in that it treats of extended wave functions, so an electron in a hydrogen atom, for example, is in some sense everywhere at once![1] But things are not that simple. There are three issues involved: (a) Are electrons 'spread out'? (b) If they are, do they nevertheless have local properties, such as propensities to be at particular locations, the spreadingoutedness reflecting the fact that a whole spectrum of such properties can be possessed by the electron at the same time? (c) Can these local properties 'act' on one another instantaneously at a spatial separation (speaking non relatavistically for the time being)?

The puzzle starts with (a). When you measure the position of an electron you find it somewhere, so it is tempting to think that the sense of 'nonlocal' in (a) reflects an ignorance of where the electron is rather than an 'ontological' spreading out. But if you answer 'yes' to (a) then (b) also gets a

'yes', so the properties themselves are not 'spread out'. (c) trivially gets the answer 'no', if you answer 'no' to (a) but 'yes' if you go along with 'yes' to (a) and (b). This is really the famous issue of the projection postulate. If I change the propensity 'here' to one, the propensity everywhere else goes to zero, and that looks like action-at-a-distance, ~~but remember we do not have to answer 'yes' to (a).~~

Then, what about the famous two-slit experiment? If I answer 'yes' to (a), there does not seem to be any extra nonlocality involved in the effect of opening and shutting the second slit. If I answer 'no' to (a) then it is not clear whether any instantaneous effects can be propagated - it depends on the detailed hidden-variable dynamics of the experiment.

So, it is all very confusing. Clarification began in 1935 with the Einstein-Podolsky-Rosen (EPR) argument for the incompleteness of the quantum - mechanical formalism. The EPR argument deals with the quantum mechanics of two-body systems. This opens up the possibility of a much more precise discussion, but also new sorts of issues arise: (A) If you have two distinguishable particles in QM, like an electron and a proton, does each of them have individual properties?[2] If the answer to that is 'yes' then we can go on to ask the question (B): Can these properties ~~act~~ be affected nonlocally ~~on one another?~~ by events occurring even at spacelike separation EPR assumed the answer to (A) was 'yes' and proceeded to pose a dilemma:

The formalism of QM => (B) gets answer 'yes'

or (a) gets answer 'no'

EPR assumed (B) is answered 'no' and hence argued that (a) gets the answer 'no'.

The crunch came in 1964 when Bell showed that, if the answer to (a) is 'no', then the answer to (B) is 'yes'! So the conclusion of the two arguments put together is:

> The answer to (B) is 'yes'.

but since the argument is predicated on assuming that the answer to (A) is 'yes', the conclusion should really be rendered as

> * the answer to (B) is 'yes'
> or the answer to (A) is 'no'

The first disjunct of * offers us action-at-a-distance between individual properties. The second disjunct offer us 'nonseparability', a holistic involvement of the two particles, in which not all their properties can be attached individually to each particle. But unfortunately that is not the end of the story, because Bell's argument brought in some other assumptions, call them collectively P, so the conclusion is really:

> ** Either P is false or we have nonlocality (in the precise sense that we have either action-at-a-distance or nonseparability).

So if we want to avoid the unpalatable conclusion of nonlocality then we can always escape by denying P. So we had better delve into P. We must be a little more precise about the details of Bell's argument.

We have introduced (a) in the version: Are electrons spread out? But the question is much more general. Do superimposed states 'spread' properties generally among the properties appropriate to the component states? So far we have talked about position, but for a general observable Q, in a superposition of eigenstates of the associated operator $\hat{Q}$, what can be said about the value of Q? The original EPR argument did apply to the positions of two particles and purported to show that in an appropriately chosen superimposed state, the positions of the particles were sharp, i.e. not, in any sense, spread out. But in 1951 Bohm[3] developed a version of the EPR argument which used the spin components of two spin-½ particles projected along a particular direction, say the Z-direction, in a state, the so-called singlet state, involving a superposition of products of eigenstates of the spin-projections along the Z-axis, and demonstrated that, even in such a superposition, the spin-projections of each particle had a definite sharp value.

Bell employed the Bohm version of the EPR argument, but now considered spin-projections for the two particles along different directions. Assuming the values of the spin-projections were determined by the 'hidden' variables describing the 'complete' state of the source and that correlations between spin-projections predicted by QM could be expressed as a weighted average over the products of the spin-projections for given values of the hidden variables, he derived an inequality, the so-called Bell inequality between correlation coefficients, which was violated by the QM predictions, and

also, as it turned out, by experiment.

So one can now identify two elements in the additional assumptions P, used by Bell in his original 1964 paper to arrive at his conclusion. First a probability structure was laid out, exhibiting the values of the spin-projections as random variables over a classic probability space equipped with a probability measure expressing our ignorance as to the exact hidden state of the source. Secondly there was an assumption of determinism.

In particular the first assumption identified a joint probability distribution for the values of spin-projections along different directions for the same particle although, according to the usual interpretation of the uncertainty principle, such components for the same particle could never be measured simultaneously. We shall call this particular assumption JD (for joint distribution).

There have been two major controversies in the literature arising out of Bell's argument:
(1) Can one get the argument off the ground if one denies JD?
(2) Can one get the argument off the ground if one denies determinism?

With regard to JD, things looked distinctly promising when a new proof of the Bell inequality was developed by Stapp (1971) and Eberhard (1977), which did not use the machinery of formal probability spaces at all, but expressed the relevant

correlations directly in terms of limiting frequencies in a long run of repetitions of the experiment. Making appropriate randomness assumptions about these sequences, it appeared that one could derive the Bell inequality without committing oneself to JD. This point was particularly stressed by Redhead (1983, 1987). But meanwhile Fine (1982) had claimed to show that satisfaction of the Bell inequality was a sufficient condition for JD to obtain[4] and had claimed, contra Redhead, that the Stapp-Eberhard 'proof' must have a concealed premiss equivalent to JD, so the violation of the Bell inequality could be imputed to a failure of JD, rather than any unacceptable violation of locality. The situation here was clarified in the work of Svetlichny, Redhead, Brown and Butterfield (1988), who pointed out that Fine's mathematics showed only that satisfaction of the Bell inequality was sufficient for the existence of a classical probability space returning the measured experimental joint distributions as marginals. This space would have relative frequency models satisfying JD, but there was no argument to show that the relative frequencies generated in the real world should conform to these purely mathematical models. So it was perfectly consistent to claim both the denial of JD and the satisfaction of the Bell inequality, and Fine's maneouvre failed to vitiate the Stapp-Eberhard proof.[5]

With regard to the second controversy concerning determinism, Redhead argued against Stapp that determinism was a concealed assumption in the Stapp-Eberhard proof.[6] The issue here related to the necessity of using counterfactual formulations

in the Stapp-Eberhard proof. This turned on the question, what can one say about the possible result of a measurement that one could have performed but did not? Could these counterfactual results for one particle vary according to what measurement was carried out on the remote particle? If the measurement results were generated indeterministically Redhead claimed such variation could be routinely expected, in the absence of any mysterious nonlocal influence of measurement procedures on one particle affecting the state of the remote particle. Stapp attempted to modify his proof to meet Redhead's objection, but it has been claimed by Clifton, Butterfield and Redhead (1990a) that none of Stapp's later proofs can be made to work, and that the success of the Stapp-Eberhard approach in avoiding JD was offset by its involvement with determinism.[6]

So, can one prove the Bell inequality assuming indeterminism? The answer is 'yes', and such a proof was explicitly produced by Clauser and Horne (1974) (who developed a general setting for the more restricted discussion of Bell (1971)). This proof involves giving up the idea that the measurement results are determined by the hidden variables, but allows these results to be linked stochastically to the hidden variables describing the complete state of the source and/or the measuring apparatus. Since these measurement results are no longer to be thought of as random variables on a single probability space, there is no commitment to JD (further reinforcing the argument of Svetlichny, Redhead, Brown and Butterfield).[7] But in this proof a new formulation of locality has to be provided, including a potentially controversial assumption of conditional

stochastic independence of measurement outcomes for the two particles, conditional, that is, on the precise specification of the hidden variables.[8]

A further twist to the argument was given in 1976 by Suppes and Zanotti, who showed that conditional stochastic independence was anyway compatible with the strict mirror-image correlations built into the singlet spin state used in the original 1964 proof, except in the degenerate case when determinism was restored. In point of fact it can be argued that we do not need to start with the stochastic hidden-variable framework, in order to show that for the case of strict correlation or anticorrelation, locality implies determinism. We can use the EPR argument to justify the fact that the measurement results for the distant particle cannot evolve in time stochastically, since the predicted results for the distant measurement hold good for all times subsequent to the first measurement, so stochasticity fails for the distant spins after the first measurement, but, by locality, this lack of stochasticity cannot be induced by the first measurement, so there is never any stochasticity, i.e. determinism must be true. The argument was first given in Redhead (1990) (which was written and widely circulated in 1981). See also Hellman (1987).

The Algebraic Proofs

The proofs of nonlocality discussed so far have all depended on proving a Bell inequality relating certain statistical correlations and then using the fact that this inequality is violated experimentally, and also by the predictions of QM. A

quite different approach has tried to demonstrate that local hidden-variable theories are actually self-contradictory, so we would not need to do experiments, involving inevitable interpretation, with auxiliary assumptions about the working of the measuring apparatus that can always be called in question, to avoid impugning locality. This approach is generally referred to as the algebraic approach to demonstrating nonlocality, since the contradiction demonstrated amounts to showing that two unequal numbers, such as zero and one, are equal.

An algebraic contradiction for the hidden-variable description of a single system described by a state space of dimension greater than two had been demonstrated by Kochen and Specker (1967), assuming that value assignments to physical magnitudes obeyed the same functional relationships as the associated quantum-mechanical operators. The resolution of this paradox for a single system lay in recognising that the values assigned to degenerate quantities (for which there may be many states associated with a given eigenvalue) depended on the context provided by different incompatible nondegenerate quantities, of which the degenerate quantity could be regarded as a function in a well-defined mathematical sense.[9]

The route to an algebraic proof of nonlocality consisted in applying these ideas to the quantum mechanics of two separated systems. Even if a quantity, like a spin-projection along a particular direction, is nondegenerate (or maximal, as it is often referred to) when referred to the state space of a single

particle, it becomes degenerate (nonmaximal) when considered with reference to the joint state space of the two particles. So could it be that giving value assignments to uniquely prescribed locally maximal quantities could lead to a Kochen-Specker paradox, which would force the conclusion that locally maximal quantities depend in their value assignments on a holistic context provided by incompatible quantities maximal in the joint state space? If all this turned out to be the case we would have a demonstration of nonseparability in a very well-defined mathematical sense. The question was posed by Bub in his (1976), but the answer that finally emerged in 1980 was that no such contradiction could be derived.[10] Non-separability was not forced on pain of algebraic inconsistency.

In 1983 Heywood and Redhead took up the challenge and proved the following result.[11]

VR + FUNC* + OLOC + ELOC

+ Determinism => Contradiction

The principles VR, FUNC*, OLOC and ELOC express the following ideas:

VR (Value Rule): Values shall not be assigned to quantities which have a zero probability of turning up as measurement results.

FUNC*: Functional relationships between maximal observables shall be preserved by value assignments.

OLOC (Ontological locality): Locally maximal quantities are uniquely specified, independently of a holistic context.

ELOC (Environmental locality): Value assignments to locally maximal quantities for one particle are not affected by any

physical manipulation of the environment of the remote particle.

Heywood and Redhead showed then that, modulo the other assumptions in the proof. OLOC and/or ELOC must be violated. Essentially, Bub's idea had been to demonstrate a violation of OLOC on its own. This, as we have seen, could not be done, and the weaker conclusion was all that could be established. Probability enters the proof via VR, but there is no mention of statistics or correlation functions, so this first 'quasi-algebraic' nonlocality proof seemed a good deal more direct than the original Bell-type proofs.

The Heywood-Redhead proof has since been improved in a number of directions. Firstly, it should be noted that Heywood and Redhead found it necessary to introduce value assignments for locally nonmaximal quantities to make their proof work. Stairs showed (1983) that a more elegant proof could be given under weaker conditions, requiring only consideration of value assignments to locally maximal quantities. The Stairs proof was further examined and more carefully formulated in respect of all relevant presuppositions by Brown and Svetlichny (1990).

Meanwhile Elby (1989, 1990a, 1990b) had made an extensive analysis of the quasi-algebraic proofs. He showed, for example, how even the innocuous looking FUNC* could be justified from more basic principles, and furthermore extended the scope of algebraic proofs to the case of indeterminism, employing the machinery of stochastic hidden-variable theories and the associated locality conditions, as spelled out by

Jarrett (1984), to force an algebraic contradiction out of probability assignments, rather than value assignments. In fact the algebraic proofs involve states with strict correlations, so determinism can actually be proved for these systems, as we have discussed above. So what is the force of Elby's generalisation? The answer lies in the fact that Elby does not employ a Value Rule equating zero probability with impossibility, so his stochastic generalisation of the algebraic proofs deals with a class of hidden-variable theories in which there is a residual stochasticity 'hidden' in hidden-variable states of measure zero. The proofs that strict correlation and locality implies determinism in the style of Suppes and Zanotti or the work of Redhead and of Hellman cited above all effectively rely on a version of the Value Rule.

The work of Brown and Svetlichny and of Elby brought the quasi-algebraic proofs of nonlocality to the same degree of sophistication as the Bell proofs, but, as we have stressed, with the added advantage of not requiring analysis of potentially complex correlation experiments, as in the case of the Bell approach.

A completely new turn to the developing story of nonlocality proofs was introduced by Greenberger, Horne and Zeilinger (1989) - henceforth referred to as GHZ - who produced a new algebraic proof of nonlocality, apparently quite unrelated to the Kochen-Specker paradox.[12] They considered a four-body decay problem in which an initial spin-one system decayed into

two spin-one systems, each of which in turn decayed into two spin-½ systems. Denoting the four emerging particles by A, B, C, and D, GHZ considered the spin-projections on directions at right-angles to a common line of flight of the decaying particles. Let $A(\theta_A)$ be the spin-projection for particle A along direction θ_A, similarly for $B(\theta_B)$, $C(\theta_C)$, and $D(\theta_D)$, then GHZ chose the quantum-mechanical state so that the expectation value of the product of the four spin-projections had the following property:

*** If $\theta_A + \theta_B - \theta_C - \theta_D = 0$, $< A(\theta_A) \cdot B(\theta_B) \cdot C(\theta_C) \cdot D(\theta_D) >$

$= -1$

But if $\theta_A + \theta_B - \theta_C - \theta_D = \pi$, $< A(\theta_A) \cdot B(\theta_B) \cdot C(\theta_C) \cdot D(\theta_D) >$

$= +1$

GHZ then gave an argument to show that no local hidden-variable reconstruction of these expectation value results was possible, on pain of contradiction. The GHZ proof suffered from two defects:

(1) It assumed determinism

(2) The proof, as sketched by GHZ was actually fallacious![13] (It effectively assumed that the measure of an uncountable infinity of intersections of measure-one sets was itself one!)

Both these problems were set aside in the work of Clifton, Redhead and Butterfield (1990) - hereafter CRB - who showed how to avoid the illegimate assumption in the GHZ proof, and also generalised it to the framework of stochastic hidden-variable theories. The proof proceeded in two stages. First it was shown that, subject to appropriate locality assumptions,

the satisfaction of ***required the theory to be deterministic 'almost everywhere,' as the mathematicians put it (compare the Suppes-Zanotti result referred to above for the two spin-½ correlations). Secondly, CRB showed how to produce a contradiction using a finite (indeed rather small) number of settings for θ_A, θ_B, θ_C and θ_D.

Consider the five sets of settings

	(1)	(2)	(3)	(4)	(5)
θ_A	->	↓	->	↑	↓
θ_B	->	↑	↑	->	->
θ_C	->	->	↑	↑	↑
θ_D	->	->	->	->	->

where the arrows indicate the settings along which the four spin-projections are taken, so ↑ is obtained from -> by a $\pi/2$ counterclockwise rotation, and ↓ obtained from -> by a $\pi/2$ clockwise rotation.

Then satisfaction of ***requires (almost everywhere)

$$A(->) \cdot B(->) \cdot C(->) \cdot D(->) = -1 \quad (1)$$

$$A(↓) \cdot B(↑) \cdot C(->) \cdot D(->) = -1 \quad (2)$$

$$A(->) \cdot B(↑) \cdot C(↑) \cdot D(->) = -1 \quad (3)$$

$$A(↑) \cdot B(->) \cdot C(↑) \cdot D(->) = -1 \quad (4)$$

$$A(↓) \cdot B(->) \cdot C(↑) \cdot D(->) = +1 \quad (5)$$

where each factor has the value ±1, in the units being used in the calculation.

From (1) and (2)

$$A(->) \cdot B(->) = A(↓) \cdot B(↑) \quad (6)$$

From (1) and (3)

$$B(->) \cdot C(->) = B(↑) \quad C(↑) \quad (7)$$

From (1) and (4)

$$A(\rightarrow) \cdot C(\rightarrow) = A(\uparrow) \cdot C(\uparrow) \qquad (8)$$

Multiplying (6), (7) and (8) yields

$$I = A(\downarrow) \cdot A(\uparrow)$$

or multiplying both sides by $A(\downarrow)$

$$A(\downarrow) = A(\uparrow) \qquad (9)$$

But (4) and (5) show that

$$A(\downarrow) = -A(\uparrow) \qquad (10)$$

(9) and (10) demonstrate the required contradiction.

An interesting feature of the proof is that (10) can actually be demonstrated, instead of relying on some principle like FUNC* (remember by the very definition of spin-projection that the operators associated with $A(\uparrow)$ and $A(\downarrow)$ are negatively related).

It should also be noted that the proof involves consideration of settings for which the spin-projections are almost everywhere exactly correlated or anticorrelated. That is to say, for example, knowing the results of measuring $A(\rightarrow)$, $B(\rightarrow)$, $C(\rightarrow)$, then Eq.(1) enables us to predict almost everywhere (i.e. with probability one) the result of measuring $D(\rightarrow)$, and similarly for Eqs.(2), (3), (4) and (5), any three measurements enable the fourth to be predicted. GHZ stress that this is just the situation in which EPR and indeed Bohr would allow the existence of elements of reality by virtue of perfect predictability. GHZ go on to claim that their argument is an effective counter to Bohr's response to EPR,[14] effectively that elements of reality are only demonstrated where the results of measurement are predicted rather than merely

Speaker B

Mermin's proof has been reworked with much more careful attention to all concealed assumptions by Stairs and Redhead (1996). It is also interesting to note that Mermin's proof can be generalized to the case of N particles, and the question posed, does the proof go through even in the case of an infinite number of particles? This problem has been answered by Pagonis and Clifton and Redhead (1991) who find that the proof of perfect correlations actually breaks down in the classical limit of an infinite number of particles. This confirms the intuition that the nonlocality under discussion is a peculiarity of QM phenomena.

predictable. CRB reject the cogency of this argument. There is no single context of measurement in which the existence of elements of reality corresponding to all the quantities used in obtaining the contradiction can be demonstrated on grounds of predictedness, rather than mere predictability, so the Bohr response remains as a possible option.[15] But the holistic aspect of Bohr's context of measurement on one particle as prescribing elements of reality for the remote particle (in the original EPR set-up) already produces a nonlocality, at any rate analogous to violation of the Heywood-Redhead OLOC principle.

~~In passing~~ One may note that the CRB contradiction involves a fixed setting for the fourth particle. So one suspects that a similar type of argument could be produced using a three-body rather than a four-body decay. That this is so has been shown in explicit detail by Mermin (1990), (1990a).[16] (insertion B)

So far we have talked as though quantities like A(->), B(↑) etc. were elements of reality discovered by the appropriate measurement procedure. This is the idea of faithful measurement and it has been argued (Redhead (1989a) p.99) that if measurement is not faithful, it should not properly be called measurement at all. But we can, speaking instrumentalistically, regard A(->), B(↑) etc. as just the actual measurement results (i.e. 'readings).[17] The framework of the CRB proof, allowing for stochastic involvement of measuring apparatus hidden-variables, encompasses this type of interpretation (sometimes referred to as Bohm-type

hidden-variable theories, since this sort of theory was first contemplated in the original Bohm construction in his (1952)).

We now return to the question of how the GHZ proof is related to the Kochen-Specker paradox. We follow Mermin (1990b) but present the argument in a significantly different way, that relates it directly to the other algebraic proofs. Mermin considers three spin-½ particles which are widely separated spatially.

Write σ_x^1 for the Pauli spin projection of particle number one parallel to the X-axis, σ_y^1 parallel to the Y-axis and so on. Now define

$$\begin{aligned} T_1 &= \sigma_x^1 \sigma_y^2 \sigma_y^3 \\ T_2 &= \sigma_y^1 \sigma_x^2 \sigma_y^3 \\ T_3 &= \sigma_y^1 \sigma_y^2 \sigma_x^3 \\ T_4 &= \sigma_x^1 \sigma_x^2 \sigma_x^3 \end{aligned} \tag{11}$$

It is easily checked that all these operators mutually commute and that

$$T_1^2 = T_2^2 = T_3^2 = T_4^2 = 1 \tag{12}$$

and also $$T_4 = -T_1 T_2 T_3 \tag{13}$$

From (12) and (13) we have

$$T_1 T_2 T_3 T_4 = -1 \tag{14}$$

Denote the value of T_1 in the state Φ in the context of the unique orthonormal basis which simultaneously diagonalizes T_1, T_2 and T_3 by $[T_1]^{\Phi}_{T_1 T_2 T_3}$

The Relativistic EPR Argument

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1 Introduction

At first glance, the realist interpretations of quantum mechanics such as Bohm's offer many advantages over standard interpretations of the theory. In particular, they give a clear, intuitive picture of many potentially paradoxical physical situations, such as the two-slit experiment and the phenomenon of barrier penetration. At the same time, their chief drawback—a form of nonlocality that seems to conflict with the constraints of relativity theory—is apparently shared by the standard, 'antirealist' interpretations that reject hidden variables and assume completeness, as was demonstrated by the original Einstein-Podolsky-Rosen argument. However, while the Bell argument that establishes nonlocality for realistic interpretations such as Bohm's has been formulated in a relativistic context (Landau (1987); Summers and Werner (1985)), there is no well-established relativistic formulation of the EPR argument. In the absence of such a formulation, it seems hasty to conclude that the tension between the standard interpretations and relativity theory is just as great as that between Bohmian interpretations and relativity. Clearly, if a relativistic formulation of EPR could be given that did *not* entail nonlocality, antirealist interpretations would have an advantage over the Bohmian interpretation.

We now

~~The present paper~~ will investigate the possibility of a relativistic formulation of the EPR argument. ~~In Section 2,~~ First we will review the standard non-relativistic version of the EPR argument and consider the problematics of translating it into a relativistic context. We will pay particular attention to the need for a reformulation of the so-called reality criterion. ~~In section 3~~ Then, we introduce one such reformulated reality criterion, due to Ghirardi and Grassi (1994), and we show how it is applied to the non-relativistic EPR argument. ~~In section 4,~~ Next we discuss the application of the new reality criterion in a relativistic context and point out a flaw in Ghirardi and Grassi's argument that seems to us to undermine their conclusion of peaceful co-existence between quantum mechanics and special relativity. Finally, ~~in section 5~~, we engage issues related to the evaluation of counterfactuals that reveal a hidden assumption of determinism in Ghirardi and Grassi's proof, while offering a way of salvaging their conclusion. ~~In section 6, we review and summarize our own conclusions.~~

~~2. Non-Relativistic~~ EPR

A relativistic version of the EPR argument must differ from the non-relativistic version in two principal ways. First, the particle states must be described by a relativistic wavefunction. The details don't concern us here; we need only require that the wavefunction preserve the maximal, mirror-image correlations of the non-relativistic singlet state. And indeed, ~~one of us~~ Redhead (1995)[18] has recently demonstrated the existence of maximal correlations in the vacuum state of relativistic algebraic quantum field theory. Second, the argument must not depend on the existence of absolute time ordering between the measurement events on the left and right wings of the system, for in the relativistic argument these may be space-like separated. As it turns out, the non-relativistic version of the argument *does* invoke absolute time ordering.

To see how to get around this problem, we must briefly review the standard formulation of the incompleteness argument.

For EPR, a necessary condition for the completeness of a theory is that every element of physical reality have a counterpart in the theory. To demonstrate that quantum mechanics is incomplete, EPR need simply point to an element of physical reality that does not have a counterpart in the theory. In this vein, they consider measurements on a pair of scattered particles with correlated position and momentum, but Bohm's formulation of the argument (1951), in terms of a pair of oppositely moving, singlet-state, spin-1/2 decay products of a spin-0 particle, is conceptually simpler. In this case, the formalism of quantum mechanics demands a strict correlation between the spin components of the two spatially separated particles, such that a measurement of, say, the Z-component of spin of one particle allows one to predict with certainty the outcome of the same measurement on the distant particle. This ability to predict with certainty, or at least probability one, the outcome of a measurement is precisely the EPR criterion for the existence of an element of reality at the as-yet-unmeasured particle. By invoking one final assumption, a locality assumption stating that elements of reality pertaining to one system cannot be affected by measurements performed 'at a distance' on another system, EPR can establish that the element of reality at the unmeasured particle must have existed even *before* the measurement was performed at the distant particle. But the quantum-mechanical formalism describes the particles at this point with the singlet state, and thus has no counterpart for the element of reality at the unmeasured particle. It follows that the quantum-mechanical description was incomplete.[19] Schematically,

QM Formalism ∧ Locality → ~ Completeness

Alternatively, if one assumes Completeness, the argument may be rearranged as a proof of nonlocality:

QM Formalism ∧ Completeness → ~ Locality

The problematic assumption of absolute time ordering entered the argument in the reality criterion, which turns on the possibility of predicting with certainty the outcome of a measurement along one wing *subsequent* to having obtained the result of a measurement along the other. Of course, for space-like separated events, notions like precedence and subsequence are reference-frame dependent, not absolute. So to translate the EPR argument to a relativistic context requires a modified criterion for the attribution of elements of reality that is not contingent on the time ordering of the measurement events. In a recent paper, Ghirardi and Grassi (1994) have undertaken to formulate just such a criterion, and thus to salvage the EPR argument in a relativistic framework. For the sake of clarity, we shall first describe how this criterion applies to the non-relativistic version of the argument.

3. The Counterfactual Criterion and Non-Relativistic EPR

Ghirardi and Grassi's criterion rests on the truth of certain classes of counterfactual statements[3]—statements of the form 'if φ were true, then ψ would be true', where the antecedent φ is in general known to be false. In particular, they wish to 'link...the attribution at time t of the property corresponding to [observable A having value a] to the truth of the counterfactual assertion: if a measurement of [A] were performed at time t, then the outcome would be [a].' In order to evaluate the truth of such statements, they call on the work of David Lewis (1973):

Let us denote the counterfactual 'if φ were true then ψ would be true' as '$\varphi \Box\!\!\rightarrow \psi$' Then Lewis proposes the following truth condition: $\varphi \Box\!\!\rightarrow \psi$ is true at world w if either (i) there are no possible worlds at which φ is true or (ii) some world where both φ and ψ are true is more similar ('closer') to w than any world in which φ is true and ψ is false. Obviously one has to specify the possible worlds one is taking into account; this is done by assigning to each world w a set of worlds S_w called the sphere of accessibility around w.

With this criterion in hand, Ghirardi and Grassi can now run the *non-relativistic* EPR argument essentially as before. They assume a measurement of property A is performed on the right-hand system at time t_R, yielding a specific result a. To ascertain whether an element of reality corresponding to property $A = a'$ exists at the left-hand system, they must assess the truth of the counterfactual assertion: 'if I were to perform a measurement of property A at the left-hand system at time t_L, I would obtain the result a'.' In the non-relativistic case, the truth of this counterfactual assertion follows naturally from the presence of absolute time ordering. For if $t_R < t_L$, then the outcome of the right-hand measurement can be assumed to be the same in all of the 'accessible' (most similar) worlds used to evaluate the counterfactual, because it is strictly in the past of the counterfactual's antecedent. The strict correlation laws of quantum mechanics, also assumed to hold in all accessible worlds, then demand that the result of a measurement on the left wing also be fixed in all possible worlds (specifically, the laws require that $a' = -a$). Thus the counterfactual is true, and an element of reality can be said to exist at the left-hand system. From here, the argument unrolls in the usual way, and by supplementing this reality criterion with a locality assumption (they call it G-Loc, after Galileo), Ghirardi and Grassi can deduce that quantum mechanics is incomplete. Once again, we can represent their argument schematically by

QM Formalism $\wedge$ G-Loc $\rightarrow \sim$ Completeness

or

QM Formalism ∧ Completeness → ~ G-Loc

While these conclusions seem sound, the locality principle, G-Loc, bears further investigation. It reads: "A system cannot be affected by actions on a system from which it is isolated. In particular, elements of physical reality of a system cannot be influenced by actions on systems from which it is isolated." An examination of the structure of Ghirardi and Grassi's argument reveals that they make use not of the general principle stated but of a special case of this general principle, viz that elements of reality cannot be brought into existence 'at a distance.' It is this special case of G-Loc, call it ER-Loc (for elements of reality) that enters toward the end of the argument to establish that the measurement at the right wing could not have created an element of reality at the left wing and thus that it must have existed prior to the measurement at the right wing, when the quantum formalism said the particles were in the singlet state. Thus they conclude that quantum mechanics is incomplete. All is well so far, but when one turns the argument around, assuming completeness and dispensing with locality, one must ask, can one be more precise as to which locality principle should be given up: the principle they label G-Loc, or the special case ER-Loc? Indeed it is the latter, for only it entered into the argument. As it turns out the distinction between G-Loc and ER-Loc does not affect their conclusions in the non-relativistic case, because the conclusion they choose to highlight—the creation of elements of reality at a distance—is precisely one that does follow from dispensing only with ER-Loc.

4. Relativistic EPR

In the relativistic case, however, more care must be taken with the statement of the locality principle, this time called L-Loc (after Lorentz by

Ghirardi and Grassi), because a locality principle must enter at the very beginning of the argument as well as in the usual way at the end. The argument begins in the same way as in the non-relativistic case, with the occurrence of a measurement on the right-hand side, but now the absence of absolute time ordering means the result of this measurement can no longer tacitly be assumed to be the same in all the accessible worlds used to evaluate the element-of-reality counterfactual at the left-hand side. Locality must be invoked to establish the independence of the outcome of the right-hand measurement from the occurrence of the measurement at the left. This done, Ghirardi and Grassi then demonstrate the existence of an element of reality at the left-hand side following the same reasoning as above. From here, the argument unrolls once again in the usual way and locality makes a second appearance in its familiar place at the end of the argument. In this way, Ghirardi and Grassi can again prove that standard quantum mechanics plus 'locality' implies incompleteness.

But there are two quite distinct cases of L-Loc that are actually being employed, one used in getting the argument started and the other appearing in the conclusion. Ghirardi and Grassi define L-Loc as the following: "An event cannot be influenced by events in space-like separated regions. In particular, the outcome obtained in a measurement cannot be influenced by measurements performed in space-like separated regions; and analogously, possessed elements of physical reality referring to a system cannot be changed by actions taking place in space-like separated regions." As in the non-relativistic case, it is not the general principle but rather the two special cases, call them OM-Loc (for outcome of measurement) and ER-Loc (again for elements of reality), that are doing the logical work in their argument. OM-Loc affirms that the outcome of a measurement cannot be influenced by performing another measurement at space like separation, while ER-Loc affirms that elements of reality cannot be created by performing a

measurement at space-like separation Ghirardi and Grassi invoke OM-Loc at the beginning of the argument while applying the counterfactual reality criterion, as discussed above, and they invoke ER-Loc at the end of the argument, as they did in the non-relativistic case. So if we write L-Loc = OM-Loc ∧ ER-Loc, then, schematically, their argument looks like this:

$$\text{Quantum Formalism} \wedge \text{OM-Loc} \wedge \text{ER-Loc} \rightarrow \sim \text{Completeness}$$

or

$$(*) \qquad \text{Quantum Formalism} \wedge \text{Completeness} \rightarrow \sim \text{OM-Loc} \vee \sim \text{ER-Loc}$$

Ghirardi and Grassi now argue, in effect, as follows. Assuming OM-Loc we can again demonstrate from Completeness a violation of ER-Loc, i.e. Einstein's *spooky* action-at-a-distance *creating* elements of reality at a distance. But if we don't assume OM-Loc, then we cannot deduce a violation of ER-Loc. All this is quite correct, but the price we have to pay for *not* being able to demonstrate a violation of ER-Loc is precisely that we have to accept a violation of OM-Loc!

In other words the relativistic formulation of the EPR argument does not help with the thesis of peaceful coexistence between quantum mechanics and special relativity, unless one argues that violating ER-Loc is more serious than violating OM-Loc from a relativistic point of view. This is hard to maintain since violating OM-Loc involves a case-by-case version of what Shimony refers to as violating parameter independence, and by analogy violating ER-Loc is also a form of parameter dependence. Thus we find ourselves unable to agree with Ghirardi and Grassi's claim that in the relativistic context 'the conclusion that quantum mechanics implies ... effects of parameter dependence, is not justified'.

~~If we rewrite (*) as~~

i.e. the independence of the probability of the outcome on one wing of the EPR experiment with respect to the parameters controlling the type of experiment being performed on the other wing.

~~Quantum Formalism ∧ Completeness ∧ L-Loc → ~ L-Loc~~

~~It would be easy to misconstrue Ghirardi and Grassi as illegitimately claiming that (*) cannot be used to demonstrate ~ L-Loc on the grounds that L-Loc is presupposed in the argument. This is *not* what they say,~~ but to justify peaceful coexistence, we need to identify an additional assumption omitted from (*), which, if challenged, could undermine the inference. This we shall proceed to investigate ~~in the next section.~~

~~5. Counterfactuals and Indeterminism~~

Recall that to run the argument in either the non-relativistic or relativistic case, Ghirardi and Grassi must establish that the outcome of, say, the right-hand measurement is the same in all accessible worlds. With this established, the correlation laws of quantum mechanics imply that the outcome of the left-hand measurement is the same in all accessible worlds, and hence establish the truth of the counterfactual assertion about the left-hand measurement result that permits the attribution of an element of reality to the left-hand system. In the non-relativistic case, the constancy of the right-hand result is a natural consequence of the absolute time ordering as discussed above; in the relativistic case, it's not so simple. A premise akin to one that Redhead, following Stapp, labels the Principle of Local Counterfactual Definiteness (PLCD) is needed to do this sort of work (Redhead 1989a ~~1987, 92~~).

In the present case, PLCD may be taken to assert that the result of an experiment which *could* be performed on a microscopic system has a definite value that does not depend on the occurrence of a measurement at a distant apparatus. Ghirardi and Grassi implicitly assume that PLCD is licensed by their locality principle, for they invoke only OM-Loc to establish the constancy of the right-hand outcome in all accessible worlds. But Redhead argues that PLCD does *not* follow directly from any typical locality principle,

certainly not from one like OM-Loc, which asserts that the outcome obtained in a measurement cannot be influenced by measurements in space-like separated regions. The reason is quite simple: while invoking locality may prevent measurements on the left-hand system from influencing the result at the right and breaking the constancy of the accessible worlds as far as the right-hand result is concerned, it does not prevent *indeterminism* from wreaking that sort of havoc. Intuitively, we can imagine that we run the world over again, this time performing the measurement on the left-hand system. If we consider this left-hand measurement schematically as a point event with a backward light cone identical to that in the actual world, we are concerned with what will happen in the complement of the forward and backward light cones. Under indeterminism, we claim, the events in this complement (the absolute elsewhere) simply *cannot* be assumed to remain the same.

This claim is not uncontroversial, however, for Lewis himself has argued that the events in the complement can be assumed to be fixed; thus for Lewis, OM-Loc *does* licence PLCD.[23] His argument turns on a dual reading of the 'might' counterfactual implicit in our description of 're-running' the world: if I were to run the world over again and perform the left-hand measurement, the right-hand outcome *might* be different than it was in the actual world. This 'might,' he argues, could be read either as 'would be possible' or as 'not would not,' but that the first reading does not contradict the negation of the second reading. We are not enamoured of this slippery semantic solution to the problem which is forced on Lewis by his insistence on including events in the absolute elsewhere in assessing the similarity relation between worlds. We thus maintain (albeit controversially) that Ghirardi and Grassi need both OM-Loc and an assumption of determinism to get their argument off the ground. Schematically, (*) is replaced by

(**) Quantum Formalism ∧ Completeness ∧ Determinism → ~OM-Loc ∨ ~ER-Loc

It seems, then, that Ghirardi and Grassi's reformulation of the EPR argument in a relativistic context may be less general than they would have us believe, for its scope is limited to deterministic systems.*

Conclusion contd as insertion C from p. 36

~~6 Conclusion~~

We have examined Ghirardi and Grassi's attempt to reformulate the EPR argument in a relativistic context and argued that it is flawed by an ambiguously stated locality principle and a hidden assumption of determinism. By making explicit the logical structure of their argument, we have undermined the conclusion that in the relativistic case the existence of action-at-a-distance is not a valid deduction from the EPR argument.

This conclusion can, however, be rescued if an additional hidden assumption of determinism is exposed. Assuming indeterminism then, we claim to avoid the EPR inference to action-at-a-distance, and the concomitant challenge to peaceful co-existence between quantum mechanics and special relativity. Thus we end up agreeing with Ghirardi and Grassi, but for different reasons from the ones they present in their paper.

~~To avoid misunderstanding,~~ We should stress that we have been concerned in this ~~paper~~ discussion with violations of locality principles such as OM-Loc and ER-Loc which actually figure explicitly or implicitly in the original EPR argument and its extension by Ghirardi and Grassi.

Even if, as we have argued, violations of either ER-Loc or OM-Loc cannot be derived under an assumption of indeterminism, there remains of course the question of how to interpret the violation of outcome dependence, ~~as Shimony calls it. This is the dependence of the probability of the result of a~~ measurement on one wing of the EPR experiment on the *outcome* ~~of the measurement on the other wing~~. Assuming Completeness, outcome

dependence famously follows. In the EPR set-up this means that when measurements are performed at space-like separation on the two wings of the experiment the results are mirror-image correlated. As one potentiality gets actualized on the left, say, how does this happen exactly in tandem with the opposite result on the right? Are we faced with a causal effect, viz result-to-result causation, so peaceful coexistence with relativity is still challenged, even if OM-Loc and ER-Loc are not violated?

There are two answers that may be given to this question. The first, that is favoured by Shimony, points to the impossibility of utilizing outcome dependence for the purposes of signalling and Shimony claims this is sufficient to meet the putative peaceful coexistence challenge arising from outcome dependence. The second line is the one favoured by Redhead, who in a series of papers, has claimed that result-to-result dependence cannot be seen as a causal dependence because it fails to satisfy an additional necessary condition for causal dependence termed 'robustness' by Redhead.[12]

If these arguments are accepted then the results ~~of the present paper~~ may be seen as closing *additional* gaps in the peaceful coexistence argument arising from the possibility of violating OM-Loc and ER-Loc over and above the fact of outcome dependence. But it must be stressed that the mysterious harmony of the result-to-result correlations remains arguably 'spooky' even if it does not involve *causal* dependence.

Another distinguishing feature of this harmony is its symmetrical character, quite unlike the asymmetry that one would normally want to ascribe to a causal connection. Shimony's phrase 'passion-at-a-distance' seems exactly the right one to capture what is going on, even if one concedes that the mystery of the EPR correlations is not eliminated merely by introducing an apt nomenclature.

~~It is a privilege to dedicate this paper to our friend and mentor, Abner Shimony.~~

[12] Similar issues involving NO-signalling or non-robustness may be invoked as in the 'realist' option discussed by the

For the antirealist often the role of measurement is to actualize potentialities. If there are no measurements, then there are no ~~actualities~~ actualities! The observer is particularly relevant to cosmological applications of quantum mechanics, where there is nothing 'outside' the Universe to serve as a measuring device!

So, from the cosmological perspective, we can argue that the realist option is untenable to be honest.

And how we can argue that the non-separability approach as exhibited in Bell's theorem as explained by denying the OLOC principle may in the end, be the best way to understanding the peculiar features of entangled states in QM. This is due

afterwood departed, ~~e.g.~~ for Oporto,
in Portland (1995)

Cont'd follow with Quarter E Jean
p. ~~Little~~ 36

attribution of an element of reality to any one spin component would now depend on measuring the relevant components of spin for all the others, which is clearly an infeasible task on the hypothesis that the total number of spins is infinite, and adopting an operational point of view as to what can actually be done in the laboratory.

But suppose we attribute values to all the spin-projections on a realist construal of the infinite spin system, so that we are not directly employing the EPR criterion for identifying elements of reality, even in the counterfactual sense we had found necessary in formulating the GHZ argument along EPR lines. Then again we cannot formulate the contradiction in the way we have described since it depends on knowing whether N is even or odd, since although the contradiction is obtainable in either case, the proof must start by making the distinction. But for N infinite we cannot make the necessary distinction, so the formulation of the contradiction fails.

We believe this discontinuous behaviour as $N \to \infty$ to be the analogue of the Garg-Mermin results for the present approach, and it is certainly a satisfactory feature of the quasi-algebraic proofs that global contradictions cannot apparently be formulated for infinite systems.

Conclusion

So where does the discussion of nonlocality in quantum mechanics rest in the light of the various proofs whose ideas we have been sketching?

~~Firstly, we should stress that the problem is not mitigated by~~

relatavistic formulations which incorporate a locality axiom in the form that local observables at space-like separation must be associated with commuting operators. This requirement guarantees only that statistical effects cannot be propagated superluminally (see below), but leaves open the question of what happens on a particular occasion [18]. Taking first the realist option, if we assume determinism, or restrict the discussion to cases of strict correlation or anticorrelation where we can derive determinism on plausible assumptions, there seems very little scope for avoiding the conclusion of nonlocality for any 'realist' reconstruction of QM. But experimentally we never observe absolutely strict correlations, so it may be argued that we should not be dealing with this ideal case, but discussions of nonlocality should be based on the experimentally realistic non-ideal case. I am not convinced by this argument, since idealization is an essential aspect of any scientific theorizing. Be that as it may, the assumption of determinism for the non-ideal case where correlations are less than perfect, may well be suspect. In such cases we are forced, as we have seen, to go to the stochastic hidden-variable framework, and much of the recent discussion has focussed on the significance of violating the locality assumptions involved in this framework. Following Jarrett (1984) these break down into two classes.

(in which all observables have sharp values at all times)

(1) Independence of the probability for a particular outcome of measurement on one particle conditionalized on the collective hidden variables, on the type of measurement being carried out on a remote particle; this is Shimony's parameter independence;

(2) Independence of the probability for a particular outcome of measurement on one particle, conditionalized on the collective hidden variables, on the outcome of measurement carried out on a remote particle. This is what Shimony calls outcome independence.

Violation of (1) has been generally held to mark probabilistic causal dependence between the outcome of a local measurement and the 'setting' of a remote piece of apparatus, in prima facie conflict with standard interpretations of special relativity as prohibiting causal links between space-like separated events. Violation of (2) has led to more controversy. It seems to demonstrate that the precise specification of the state of the source, or more generally of the particles before the measurements are undertaken, cannot be regarded as a common cause of the measurement outcomes. And this in turn suggests that such a common cause must be overlaid by a direct causal connection between the events consisting of the measurement results on distant particles obtaining in the way they actually do. This view has been challenged by Redhead (1986, 1989a, 1989b, 1993) who proposes to interpret violation of (2), not in terms of a combination of common cause and direct cause, in the way proposed, but in terms of a non-causal direct dependence between measurement outcomes which lacks the necessary 'robustness' in respect of how the measurement results are brought about, to merit description as a causal connection.[24] This approach gives up the stochastic hidden-variable framework in favour of trying to understand the correlations between distant events in terms of a harmony-at-a-distance, or, as Shimony describes it in his (1984), a passion-at-a-distance.

This idea ties in with, but is really quite distinct from, the fact that violation of (2) cannot be used to transmit

signals between distant locations, since the necessity to recover quantum-mechanical probability distributions by averaging over the hidden variables, means that we have no way of controlling the local marginal distributions for the results of measurement on one particle, by varying the type of measurement performed on distant particles.

Insertion E on p. 31

The whole issue of nonlocality in quantum mechanics is one of considerable metaphysical subtlety and of ongoing debate. It is hoped that the present paper has served to highlight some of the more important landmarks, while avoiding the escalating technical complexity of many of the recent contributions.

I acknowledge the benefit of fruitful discussions on these topics with members past and present of the Philosophy of Physics Group at Cambridge. I would particularly like to mention Jeremy Butterfield, Rob Clifton, Andrew Elby, Guido Bacciagaluppi, Thomas Brower, Meir Hemo, Patrick La Riviere, Constantine Pagonis, Adam Stacho and Fabien Wagner, who have patiently educated me in so many ways.

The no-signalling result is often cited to defuse the tension between SR's Constraints of special relativity, but, at a deeper level, Jarrett's nonrobustness argument may be presented. [Turning to the entangled states,

(Insertion C from p 28.) ⇒

Footnotes

1. Indeed, the 'range' of a wave function may be much longer than the 'range' of interaction, as in the case of so-called Efimov states in nuclear physics.

2. In the case of indistinguishable particles question (A) becomes more controversial since the QM observables are restricted to symmetric functions of the particle labels. See French and Redhead (1988) for further discussion.

3. See Bohm (1951) p. 614ff.

4. Fine's result has been generalised to consider the conditions under which any set of experimental probability distributions can be returned as marginals on a common probability space. For a complete discussion of what has been achieved in this direction, see Pitowsky (1989).

5. Another telling objection against giving up JD is that, for states involving strict correlation or anticorrelation, joint distributions for incompatible observables on the same particle is a direct consequence of the correlation (anticorrelation), so a general prohibition on JD as applied to these important special cases, is not a viable option. Furthermore, Fine seems committed to the view that altering the experimental set-up for one particle from a Bell-conforming to a Bell-violating setting can mysteriously cause JD to obtain or not obtain on the distant particle. For full discussion see Svetlichny et al (1988).

6. See Redhead (1989) p. 90ff. for a detailed discussion.

⇒ Insertion (D) from p. 41

7. I here correct the statement made in Redhead (1990). See also Butterfield (1992a).

8. The discussion of the locality assumptions required in the derivation of Bell inequalities in the stochastic hidden-variable framework was given a very careful formulation by Jarrett (1984) - ~~see below.~~ Two ~~distinct~~ locality conditions were introduced which are now usually referred to as parameter independence and outcome independence (following Shimony). These will be defined and discussed more fully below.

9. Cp. Van Fraassen (1973).

10. See Demopoulos (1980), Bub (1980) and Humphreys (1980).

11. See Heywood and Redhead (1983). A similar approach was arrived at independently by Simon Kochen, although never published (private communication).

12. ~~Stairs (1990) has shown that the GHZ approach and the Kochen-Specker paradox do have some interesting formal affinities.~~ But see ~~also~~ Mermin (1990b). ~~This work is described below.~~

13. We stress that the GHZ proof, as published, is only a descriptive sketch, but in our opinion no proof of the sort described is rigorously possible.

14. See Bohr (1935).

15. Still another twist to the GHZ argument has been given by Pitowsky (1990). He chooses a state for a 3-particle system in which measuring the Z component of any of the spins and finding the value -1 correlates with the product of the X and Y components for the other two particles having the value +1. Applying EPR Pitowsky generates a contradiction in a now familiar way. Since all three Z measurements are compatible we can at first sight apply the EPR criterion without employing counterfactuals. But in fact the EPR criterion applied simultaneously to all 3 systems now fails because the predicted value for $\sigma_x^2\sigma_y^3$ obtained by measuring σ_3^1 for example is only valid if, counterfactually, σ_3^2 and σ_3^3 are not measured. So in all these variations of GHZ, the strict Bohrian response, preventing the demonstration of nonlocality, can be made to go through.

16. For further discussion of experimentally realizable examples for the three-body and the four-body arrangements see Greenberger, Horne, Shimony and Zeilinger (1990). These authors also independently dérived the CRB contradiction.

17. A similar interpretation is used in Brown and Svetlichny (1990), in order to avoid commitment to preexisting values.

18. For relativistic formulations of the Bell inequality see Landau (1987) and Summers and Werner (1987). A relativistic formulation of the EPR argument has been provided by Smith and Weingard (1987). An important issue here is the difficult question of the localisation of relativistic particles.

For a unified treatment of the relativistic EPR and [illegible] arguments of Redhead and Wagner (1998) 4

[1] See Redhead (1995). The argument actually applies more generally to any state of bounded energy; see also Redhead (1994).

[2] We follow here a streamlined version of the EPR argument, as introduced by Redhead (1987) and Hellman (1987). Historically this version of the argument seems to have been known to Einstein. See, for example, Fine (1986). This is also the version used by Ghirardi and Grassi in the paper under discussion.

[3] An analysis of the EPR argument using counterfactuals, though not specifically in the context of a relativistic reformulation, has been undertaken by Wessels (1981). She seeks to uncover the full logical structure of the EPR argument by formulating the original paper's somewhat ambiguous reality criterion in precise modal terms. Among four possible modal readings of the EPR reality criterion, she lists a counterfactual reading similar to Ghirardi and Grassi's, which is the one we also adopt in this paper. the present work

[4] A discussion of the EPR set-up in a relativistic context has also been provided by G. Smith and R. Weingard (1987). They argue that any relativistic formulation of EPR should employ a relativistic correlated state. They derive such a state and demonstrate the relativistic invariance of the correlations. However they fail to pursue the analysis beyond the existence of the correlations, i.e. to develop the full EPR argument. Three-particle versions of the EPR argument in a relativistic context have also been considered recently in the literature. See, for example, Clifton, Pagonis, and Pitowsky (1992). For a critique of their conclusions, see Pagonis, Redhead, and La Rivière (1996). cf also Pitowsky (1994).

[5] See Shimony (1993), p. 138 for his preferred terminology in this matter. for more discussion of this terminology see below.

[6] D. Lewis, private communication. See also Lewis (1986).

[7] This whole topic of evaluating counterfactuals under an assumption of indeterminism has been the subject of a long-running debate between H. Stapp and M. Redhead. See in particular Clifton, Butterfield, and Redhead (1990). The most up-to-date list of references on the topic can be found in Clifton and Dickson (1994) and Stapp (1994).

As we have already noted [illegible] Question 6 Din footnote 6 on p. 38

Localisation is essentially a frame-dependent notion. For a comprehensive account of these matters, together with an attempt to restore an invariant concept of localisation by recognising an explicit hyperplane dependence of relativistic state vectors see Fleming (1985).

19. For a careful discussion of these issues see Butterfield (1990b).

20. For further discussion of the no-signalling results see Redhead (1989a) p.113ff. and other references detailed there, and also Eberhard and Ross (1989).

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Cops for authors please

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